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OPTICAL FIBER AND SYSTEM CONTAINING SAME

Cross-Reference to Related Applications

[0001] This application is a continuation of International Application No. PCT/US02/14992, which has an international filing date of May 13, 2002, and is entitled "Optical Fiber and System Containing Same", and which in turn claims priority to United States Provisional Patent Application Serial No. 60/291,168, which was filed May 15, 2001 and is also entitled "Optical Fiber and System Containing Same". The foregoing applications are incorporated herein by reference.

Technical Field

[0002] The invention relates to optical fibers (e.g., fiber amplifiers and fiber lasers), and systems containing optical fibers (e.g., fiber amplifier systems and fiber laser systems).

Background

[0003] Certain optical fibers can be used as fiber amplifiers or fiber lasers.

[0004] Fiber amplifiers are typically used to amplify an input signal. Often, the input signal and a pump signal are combined and passed through the fiber amplifier to amplify the signal at the input wavelength. The amplified signal at the input wavelength can then be isolated from the signal at undesired wavelengths.

[0005] Raman fiber lasers can be used, for example, as energy sources. In general, Raman fiber lasers include a pump source coupled to a fiber, such as an optical fiber, having a gain medium with an active material. Energy emitted nom the pump source at a certain wavelength λ_p, commonly referred to as the pump energy, is coupled into the fiber. As the pump energy interacts with the active material in the gain medium of the fiber, one or more Raman Stokes transitions can occur within the fiber, resulting in the formation of energy within the fiber at wavelengths corresponding to the Raman Stokes shifts that occur (e.g., λ_{s1}, λ_{s2}, λ_{s3}, λ_{s4}, etc.).

[0006] Typically, a Raman fiber laser is designed so that the energy formed at one or more Raman Stokes shifts is substantially confined within the fiber. This can enhance the formation of energy within the fiber at one or more higher order Raman Stokes shifts. Often, the fiber is also designed so that at least a portion of the energy at wavelengths corresponding to predetermined, higher order Raman Stokes shifts (e.g., λ_{sx}, where x is equal to or greater than one) is allowed to exit the fiber.

Summary

[0007] In general, the invention relates to optical fibers (e.g., fiber amplifiers and fiber lasers), and systems containing optical fibers (e.g., fiber amplifier systems and fiber laser systems).

[0008] In one aspect, the invention features a fiber (e.g., a fiber laser or a fiber amplifier). The fiber includes an optical fiber having a first section and a second section coupled to the first section. The first section has a gain medium including a first active material, and the second section has a gain medium including a second active material. The second active material can be the same as or different than the first active material. The optical fiber also includes a first reflector disposed in the first section of the optical fiber. The first reflector is configured to reflect substantially all energy impinging thereon at a first wavelength. The optical fiber further includes a second reflector disposed in the optical fiber outside the first section of the optical fiber. The second reflector is configured to reflect substantially all energy impinging thereon at the first

wavelength.

[0009] In another aspect, the invention features a system that includes an energy source capable of emitting energy at a pump wavelength and a fiber (e.g., a fiber amplifier or a fiber laser). The fiber includes an optical fiber having a first section and a second section coupled to the first section. The first section has a gain medium including a first active material, and the second section has a gain medium including a second active material. The second active material can be the same as or different than the first active material. The optical fiber also includes a first reflector disposed in the first section of the optical fiber. The first reflector is configured to reflect substantially all energy impinging thereon at a first wavelength. The optical fiber further includes a second reflector disposed in the optical fiber outside the first section of the optical fiber. The second reflector is configured to reflect substantially all energy impinging thereon at the first wavelength. The energy source and the optical fiber are configured so that energy at the pump wavelength emitted by the energy source can be coupled into the optical fiber.

[0010] In another aspect, the invention features a fiber (e.g., a fiber amplifier or a fiber laser). The fiber includes an optical fiber having a first section and a second section spliced to the first section. The first section has a gain medium including a first active material, and the second section has a gain medium including a second active material. The second active material can be the same as or different from the first active material. The optical fiber also includes a first reflector disposed in the first section of the optical fiber, and the first reflector is configured to reflect substantially all energy impinging thereon at a first wavelength. The optical fiber further includes second reflector disposed in the second section of the optical fiber, and the second reflector is configured to reflect substantially all energy impinging thereon at the first wavelength. In addition, the optical fiber includes a third reflector disposed in the second section of the optical fiber. The third reflector is configured to partially reflect energy impinging thereon at a second wavelength different from the first wavelength. The optical fiber also includes a fourth reflector disposed in the second section of the optical fiber and between the first and third

reflectors. The fourth reflector is configured to reflect substantially all energy impinging thereon at the second wavelength.

[0011] In a further aspect, the invention features a fiber system (e.g., a fiber laser system or a fiber amplifier system). The system includes an energy source capable of emitting energy at a pump wavelength and a fiber. The fiber includes an optical fiber having a first section and a second section spliced to the first section. The first section has a gain medium including a first active material, and the second section has a gain medium including a second active material. The second active material can be the same as or different than the first active material. The optical fiber also includes a first reflector disposed in the first section of the optical fiber, and the first reflector is configured to reflect substantially all energy impinging thereon at a first wavelength. The optical fiber further includes a second reflector disposed in the second section of the optical fiber, and the second reflector is configured to reflect substantially all energy impinging thereon at the first wavelength. In addition, the optical fiber includes a third reflector disposed in the second section of the optical fiber. The third reflector is configured to partially reflect energy impinging thereon at a second wavelength different than the first wavelength. The optical fiber also includes a fourth reflector disposed in the second section of the optical fiber and between the first and third reflectors. The fourth reflector is configured to reflect substantially all energy impinging thereon at the second wavelength. The energy source and the optical fiber are configured so that energy at the pump wavelength emitted by the energy source can be coupled into the optical fiber.

[0012] In one aspect, the invention features a fiber (e.g., a fiber amplifier or a fiber laser) including an optical fiber having N sections. The N sections are coupled together. At least one of the N sections of the optical fiber has a gain medium with an active material. The optical fiber also includes a plurality of reflectors disposed in the optical fiber. N is an integer having a value of at least three.

[0013] N can be, for example, 3, 4, 5, 6, 7, 8, 9 or 10.

[0014] At least two of the N sections of the optical fiber can have a gain medium with an active material. The active material in one of the at least two of the N sections of the optical fiber can be different than an active material of another of the N sections of the optical fiber having a gain medium.

[0015] Each of the N sections of the optical fiber have a gain medium with an active material.

[0016] The optical fiber can have a first section with an end configured to receive energy at a wavelength λ_p. The first section of the optical fiber can have a first reflector disposed therein. The first reflector can be configured to reflect substantially all energy impinging thereon at a wavelength λ_{s1}, where $\lambda_{s1}^{-1} = \lambda_p^{-1} - \lambda_{r1}^{-1}$, (c/λ_{r1}) is the Raman Stokes shift frequency for an active material in a gain medium in the first section of the optical fiber, and c is the speed of light.

[0017] The optical fiber can have an N^{th} section with an end opposite the end of the first section. The N^{th} section of the optical fiber can have a first reflector disposed therein. The first reflector can be configured to reflect substantially all energy impinging thereon at a wavelength λ_{s1n}, where $\lambda_{s1n}^{-1} = \lambda_{s1(n-1)}^{-1} - \lambda_{rn}^{-1}$, and (c/λ_{rn}) is the Raman Stokes shift frequency for an active material in a gain medium in the N^{th} section of the optical fiber.

[0018] The N^{th} section of the optical fiber can have a second reflector disposed therein. The second reflector can be configured to partially reflect energy impinging thereon at the wavelength λ_{s1n}.

[0019] The N^{th} section of the optical fiber can have a third reflector disposed therein. The third reflector can be configured to reflect substantially all energy impinging thereon at the wavelength $\lambda_{s1(n-1)}$, where $\lambda_{s1(n-1)}^{-1} = \lambda_{s1(n-2)}^{-1} - \lambda_{r(n-1)}^{-1}$, and $(c/\lambda_{r(n-1)})$ is the Raman Stokes shift frequency for the active material in the $(N-1)^{th}$ section of the fiber.

[0020] Each of the remaining sections of the optical fiber can have two reflectors disposed therein. One of the reflectors disposed in each of the remaining sections of the optical fiber can be configured to reflect substantially all energy impinging thereon at a wavelength λ_{s1m}, where $\lambda_{s1m}^{-1} = \lambda_{s1(m-1)}^{-1} - \lambda_{rm}^{-1}$, and (c/λ_{rm}) is the Raman Stokes shift frequency for an active material in the section of the fiber.

[0021] The other reflectors can be disposed in each of the remaining sections of the optical fiber and configured to reflect substantially all energy impinging thereon at a wavelength $\lambda_{s1(m-1)}$, where $\lambda_{s1(m-1)}^{-1} = \lambda_{s1(m-2)}^{-1} - \lambda_{r(m-1)}^{-1}$, and $(c/\lambda_{r(m-1)})$ is the Raman Stokes shift frequency for an active material in an immediately preceding section of the optical fiber.

[0022] In another aspect, the invention features a fiber system (e.g., a fiber amplifier system or a fiber laser system) that includes an energy source and a fiber. The fiber includes an optical fiber having N sections. The N sections are coupled together. At least one of the N sections of the optical fiber has a gain medium with an active material. The optical fiber also includes a plurality of reflectors disposed in the optical fiber. N is an integer having a value of at least three, and the energy source and the optical fiber are configured so that energy at a wavelength emitted by the energy source can be coupled into the optical fiber.

[0023] In a further aspect, the invention features a fiber (e.g., a fiber amplifier or a fiber laser) that includes an optical fiber having at least first and second sections coupled together. The first section has a first gain medium with a first active material, and the second section has a second gain medium with a second active material different. The second active material can be the same as or different than the first active material. The optical fiber is configured to be capable of receiving energy at a first wavelength and to be capable of outputting energy at a second wavelength longer than the first wavelength. The optical fiber also includes a plurality of reflectors disposed in the optical fiber. The plurality of optical fibers are configured so that energy propagating in the optical fiber at the first wavelength undergoes at least one Raman Stokes shift to

create energy in the optical fiber at the second wavelength, and so that, when the optical fiber receives energy at the first wavelength, a power output by the optical fiber at the second wavelength is at least about 55% of a power of the energy the optical fiber receives at that first wavelength.

[0024] In another aspect, the invention features an article, such as a fiber amplifier or a fiber laser, that includes an optical fiber having multiple sections. At least two of the fiber sections have gain media that contain different active materials. The number of sections can be, for example, 3, 4, 5, 6, 7, 8, 9 or 10. Each section can have a gain medium. The gain medium in each section can contain the same or different active material as the other sections of fiber. The article can be used in a system that includes an energy source (e.g., a laser) capable of emitting energy that can be coupled into the fiber.

[0025] In some embodiments, the invention can provide a Raman fiber laser having a relatively high output power at a desired wavelength (e.g., at least about 0.1 Watt, at least about 0.5 Watt, at least about 1 Watt, at least about 2 Watts, at least about 5 Watts, at least about 10 Watts). Such a Raman fiber laser can operate, for example, under conditions of relatively high pump power (e.g., at least about 0.1 Watt, at least about 0.5 Watt, at least about 1 Watt, at least about 2 Watts, at least about 5 Watts, at least about 10 Watts).

[0026] In certain embodiments, the invention can provide a Raman fiber laser having a relatively low output power at one or more undesired wavelengths (e.g., less than about 1 Watt, less than about 0.5 Watt, less than about 0.1 Watt, less than about 0.05 Watt). Such a Raman fiber laser can operate, for example, under conditions of relatively high pump power (e.g., at least about 0.1 Watt, at least about 0.5 Watt, at least about 1 Watt, at least about 2 Watts, at least about 5 Watts, at least about 10 Watts).

[0027] In some embodiments, the invention can provide a Raman fiber laser than can convert energy entering the Raman fiber laser at a particular wavelength (e.g., a

pump wavelength) to energy exiting the Raman fiber laser at a different wavelength (e.g., a desired wavelength) with relatively high efficiency (e.g., an efficiency of: at least about 35%, at least about 40%, at least about 45%, at least about 50%, at least about 55%, at least about 60%, at least about 65%, at least about 70%, at least about 75%, at least about 80%, at least about 85%, at least about 90%, at least about 95%, at least about 98%).

[0028] In certain embodiments, the invention can provide a Raman fiber laser that can convert energy entering the Raman fiber laser at a particular wavelength (e.g., a pump wavelength) to energy exiting the Raman fiber laser at wavelengths other than a desired wavelength with relatively low efficiency (e.g., an efficiency of: at most about 45%, at most about 40%, at most about 35%, at most about 30%, at most about 25%, at most about 20%, at most about 15%, at most about 10%, at most about 5%, at most about 2%).

[0029] The Raman fiber lasers can provide these properties when the difference between the pump energy and the output energy is any value (e.g., relatively small or relatively large). In some embodiments, the difference between the pump energy and the output energy can be relatively large (e.g., at least about 100 cm^{-1}, at least about 200 cm^{-1}, at least about 500 cm^{-1}, at least about 1,000 cm^{-1}, at least about 1,250 cm^{-1}, at least about 1,500 cm^{-1}, at least about 1,750 cm^{-1}, at least about 2,000 cm^{-1}).

[0030] In certain embodiments, the fibers can be used as amplifiers rather than lasers.

[0031] Features, objects and advantages of the invention are in the description, drawings and claims.

Description of Drawings

[0032] Fig. 1 is a schematic representation of an embodiment of a Raman fiber laser system;

[0033] Figs. 2A and 2B are cross-sectional views of sections of an optical fiber;

[0034] Figs. 3A-3C are graphs demonstrating the power at three different wavelengths in an optical fiber contained in an embodiment of a Raman fiber laser system;

[0035] Fig. 4 is a schematic representation of an embodiment of a Raman fiber laser system;

[0036] Fig. 5 is a schematic representation of an embodiment of a Raman fiber laser system;

[0037] Fig. 6 is a schematic representation of an embodiment of a Raman fiber laser system;

[0038] Fig. 7 is a schematic representation of an embodiment of a Raman fiber laser system;

[0039] Fig. 8 is a schematic representation of an embodiment of a Raman fiber laser system;

[0040] Fig. 9 is a schematic representation of an embodiment of a Raman fiber laser system;

[0041] Fig. 10 is a schematic representation of an embodiment of a Raman fiber laser system;

[0042] Fig. 11 is a schematic representation of an embodiment of a Raman fiber laser system;

[0043] Fig. 12 is a schematic representation of an embodiment of a Raman fiber

laser system;

[0044] Fig. 13 is a schematic representation of an embodiment of a Raman fiber laser system; and

[0045] Fig 14 is a schematic representation of an embodiment of a fiber amplifier system.

Detailed Description

[0046] Fig. 1 shows an embodiment of a Raman fiber laser system **100** including an optical fiber **110** and a laser **120**. Laser **120** is configured so that energy emitted by laser **120** at a wavelength λ_p is coupled into optical fiber **110**. Optical fiber **110** has a first section **130** having a gain medium containing an active material and a second section **140** having a gain medium containing a different active material. Examples of active materials include GeO_2, P_2O_5, SiO_2, B_2O_3, SiO_xF_y, and the like. Sections **130** and **140** of optical fiber **110** are spliced together at region **150**.

[0047] Figs. 2A and 2B are cross-sectional views of sections **130** and **140**, respectively, of optical fiber **110**. As shown in Fig. 2A, section **130** has a gain medium **210** containing an active material, a cladding **220** (e.g., a fused silica layer) and an additional layer **230** (e.g., a polymer layer). As shown in Fig. 2B, section **140** has a gain medium **215** containing an active material, a cladding **225** (e.g., a fused silica layer) and an additional layer **235** (e.g., a polymer layer). Although Figs. 2A and 2B show a particular design of optical fiber **110**, other designs of appropriate optical fibers are known to those skilled in the art and are contemplated.

[0048] Referring to Fig. 1, optical fiber **110** also includes a first pair of reflectors **160** and **170** (e.g., a pair of fiber Bragg gratings), and a second pair of reflectors **180** and **190** (e.g., a pair of fiber Bragg gratings). Reflectors **160** and **170** are designed to reflect substantially all (e.g., about 100%) energy impinging thereon at a wavelength λ_{s1}, where $\lambda_{s1}^{-1} = \lambda_p^{-1} - \lambda_r^{-1}$, and (c/λ_r) is the Raman Stokes shift frequency for the active material in

gain medium **210**, and c is the speed of light.

[0049] Reflector **180** is designed to reflect substantially all (e.g., about 100%) energy impinging thereon at wavelength $\lambda_{s1'}$, and reflector **190** is designed to reflect a portion (e.g., less than about 98%, less than about 95%, less than about 90%, less than about 80%, less than about 70%, less than 60%, less than about 50%, less than about 40%, less than about 30%, less than about 20%, less than about 10%) of energy impinging thereon at wavelength $\lambda_{s1'}$, where $\lambda_{s1'}^{-1} = \lambda_{s1}^{-1} - \lambda_{r'}^{-1}$, and $(c/\lambda_{r'})$ is the Raman Stokes shift frequency for the active material in gain medium **215**.

[0050] Section **130** of optical fiber **110** further includes a reflector **310** (e.g., a fiber Bragg grating). Reflector **310** is designed to reflect substantially all (e.g., about 100%) energy propagating in section **130** at λ_p, which reduces (e.g., eliminates) the propagation of energy at λ_p in section **140** of fiber **110**.

[0051] Section **130** of optical fiber **110** also includes a suppressor **410**. Suppressor **410** is designed to suppress the formation of higher order Raman Stokes shifts for the active material in section **130** of fiber **110** (e.g., one or more of λ_{s2}, λ_{s3}, λ_{s4}, etc.).

[0052] With this arrangement, as energy at wavelength λ_p enters optical fiber **110**, the energy propagates through section **130** until it impinges upon reflector **310**, where it is reflected and propagates through section **130** in the reverse direction so that substantially no energy at wavelength λ_p enters section **140** of fiber **110**. Reflector **310** can increase the amount of energy at λ_{s1} propagating in fiber **110** (relative to an otherwise substantially similar system without reflector **310**) by increasing the effective optical length of energy at λ_p in section **130** of fiber **110**, which, in turn, can increase the amount of energy $\lambda_{s1'}$ propagating in section **140** of fiber **110** (see discussion below). Reflector **310** can also decrease the formation of energy at wavelength λ_u, where $\lambda_u^{-1} = \lambda_p^{-1} - \lambda_{r'}^{-1}$, (see discussion below).

[0053] As energy at wavelength λ_p propagates through section **130** in the forward and reverse directions, it creates energy at wavelength λ_{s1}. Energy at wavelength λ_{s1} propagates through sections **130** and **140** until it reaches reflector **170** where it is reflected by reflector **170**. Energy at wavelength λ_{s1} then propagates through sections **140** and **130** in the reverse direction until it reaches reflector **160** where it is reflected forward through sections **130** and **140**. Energy at wavelength λ_{s1} continues to propagate in fiber **110** in the forward and in reverse directions between reflectors **160** and **170**.

[0054] As energy at wavelength λ_{s1} propagates through section **130** of fiber **110**, it can impinge upon suppressor **410**, which reduces (e.g., substantially eliminates) the transfer of energy at wavelength λ_{s1} to energy at wavelength λ_{s2} (and/or energy at higher order Raman Stokes shifts for the active material in gain medium **210**). In some embodiments, suppressor **410** is a long period grating (LPG) having a resonance frequency of (c/λ_{s2}), where $\lambda_{s2}^{-1} = \lambda_{s1}^{-1} - \lambda_r^{-1}$. The LPG can couple energy at wavelength λ_{s2} that impinges thereon out of gain medium **210** and into cladding **220**. Cladding **220** can be formed of a material (e.g., fused silica) that dissipates energy at λ_{s2} relatively quickly. This can suppress the power of wave λ_{s2} propagating in fiber **110**, which correspondingly can suppress the formation of energy at higher order Raman Stokes shifts propagating in fiber **110**. The suppression of higher order Raman Stokes shift(s) can result in fiber **110** having a higher power of wave λ_{s1} propagating therein relative to a substantially similar system without suppressor **410**. This, in turn, can increase the amount of energy at $\lambda_{s1'}$ propagating in section **140** of fiber **110** (see discussion below).

[0055] As energy at wavelength λ_{s1} propagates through section **140** of fiber **110**, it creates energy at wavelength $\lambda_{s1'}$. Energy at wavelength $\lambda_{s1'}$ propagating in section **140** in the reverse direction is reflected by reflector **180** and then propagates through section **140** in the forward direction. Energy at wavelength $\lambda_{s1'}$ propagating through section **140** in the forward direction impinges on reflector **190**. Some of the energy at wavelength $\lambda_{s1'}$ impinging on reflector **190** is reflected by reflector **190** and then propagates through section **140** in the reverse direction, and some of the energy at wavelength $\lambda_{s1'}$ impinging

on reflector **190** passes through reflector **190** and exits fiber **110**.

[0056] Optical fiber **110** can convert energy entering fiber **110** at wavelength λ_p to energy exiting fiber **110** at wavelength $\lambda_{s1'}$ with relatively high efficiency. In certain embodiments, fiber **110** can convert at least about 35% (e.g., at least about 40%, at least about 45%, at least about 50%, at least about 55%, at least about 60%, at least about 65%, at least about 70%, at least about 75%, at least about 80%, at least about 85%, at least about 90%, at least about 95%, at least about 98%) of the energy entering fiber **110** at wavelength λ_p to energy exiting fiber **110** at wavelength $\lambda_{s1'}$.

[0057] Optical fiber **110** can convert energy entering fiber **110** at wavelength λ_p to energy exiting fiber **110** at wavelengths other than $\lambda_{s1'}$ with relatively low efficiency. In certain embodiments, fiber **110** can convert at most about 45% (e.g., at most about 40%, at most about 35%, at most about 30%, at most about 25%, at most about 20%, at most about 15%, at most about 10%, at most about 5%, at most about 2%) of the energy entering fiber **110** at wavelength λ_p to energy exiting fiber **110** at wavelengths other than $\lambda_{s1'}$.

[0058] Without wishing to be bound by theory, it is believed that these characteristics of fiber **110** can be explained using the following system of nonlinear differential equations.

$$\frac{dI_p^+}{dz} = -g_p(I_{\lambda_{s1}}^+ + I_{\lambda_{s1}}^-) \times I_p^+ - \alpha_p I_p^+ = -\frac{dI_p^-}{dz}$$

$$\frac{dI_{\lambda_{s1}}^+}{dz} = -g_1 I_{\lambda_{s1}}^+ \times (I_p^+ + I_p^-) - \alpha_1 I_{\lambda_{s1}}^+ - g_1' I_{\lambda_{s1}}^+ \times (I_{\lambda_{s1'}}^+ + I_{\lambda_{s1'}}^-) = -\frac{dI_{\lambda_{s1}}^-}{dz}$$

$$\frac{dI_{\lambda_{s1'}}^+}{dz} = g_{1'} I_{\lambda_{s1'}}^+ \times (I_{\lambda_{s1}}^+ + I_{\lambda_{s1}}^-) - \alpha_{1'} I_{\lambda_{s1'}}^+ = -\frac{dI_{\lambda_{s1'}}^-}{dz}$$

[0059] The indices $^+$ and $^-$ represent propagation in fiber **110** from left to right and from right to left, respectively. I_p, $I_{\lambda s1}$, and $I_{\lambda s1'}$ represent the intensities of energy

propagating in fiber **110** at wavelengths λ_p, λ_{s1} and $\lambda_{s1'}$, respectively. α_p, α_1 and $\alpha_{1'}$ are the loss coefficients of energy propagating in fiber **110** at wavelengths λ_p, λ_{s1} and $\lambda_{s1'}$, respectively, due to, for example, imperfections, scattering and/or splicing in fiber **110**. g_p, g_1 and $g_{1'}$ are the Raman gain coefficients, respectively, of energy propagating in fiber **110** at wavelengths λ_p, λ_{s1} and $\lambda_{s1'}$, respectively, due to power gain via stimulated Raman scattering (SRS). g'_1 is the Raman gain coefficient for the transfer of energy from λ_{s1} to $\lambda_{s1'}$. $g'_1 = (\lambda_{s1'}/\lambda_{s1})(A_{s1'}/A_{s1})(g_{1'})$, where A_{sz} is the effective area of the mode at wavelength λ_{sz}.

[0060] It is believed that for fiber **110** the second equation noted above can be decoupled into two systems of equations, with each system of equations being without a g'_1 term.

[0061] The first system of equations, which is believed to describe the propagation of energy in section **130** of fiber **110**, can be written as:

$$\frac{dI_p^+}{dz} = -g_0(I_{\lambda_{s1}}^+ + I_{\lambda_{s1}}^-) \times I_p^+ - \alpha_0 I_p^+ = -\frac{dI_p^-}{dz}$$
$$\frac{d\hat{I}_{\lambda_{s1}}^+}{dz} = g_1 \hat{I}_{\lambda_{s1}}^+ \times (I_p^+ + I_p^-) - \alpha_1 \hat{I}_{\lambda_{s1}}^+ = -\frac{d\hat{I}_{\lambda_{s1}}^-}{dz}$$

[0062] The second system of equations, which is believed to describe the propagation of energy in section **140** of fiber **110**, can be written as:

$$\frac{d\widetilde{I}_{\lambda_{s1}}^+}{dz} = -\widetilde{g}_1 \widetilde{I}_{\lambda_{s1}}^+ \times (I_{\lambda_{s1'}}^+ + I_{\lambda_{s1'}}^-) - \widetilde{\alpha}_1 I_{\lambda_{s1}}^+ = -\frac{d\widetilde{I}_{\lambda_{s1}}^-}{dz}$$
$$\frac{dI_{\lambda_{s1'}}^+}{dz} = g_2 I_{\lambda_{s1'}}^+ \times (\widetilde{I}_{\lambda_{s1}}^+ + \widetilde{I}_{\lambda_{s1'}}^-) - \alpha_2 I_{\lambda_{s1'}}^+ = -\frac{dI_{\lambda_{s1'}}^-}{dz}$$

[0063] Appropriate boundary conditions for a wave $I_{\lambda s1}$ at splice point **150** are believed to be:

$$\hat{I}^{+}_{\lambda_{s1}} = \tilde{I}^{+}_{\lambda_{s1}} \text{ and } \hat{I}^{-}_{\lambda_{s1}} = \tilde{I}^{-}_{\lambda_{s1}}$$

[0064] Figs. 3A-3C are graphs of the calculated (based on the above-noted equations) energy distribution at wavelengths λ_p, λ_{s1} and $\lambda_{s1'}$, respectively, for fiber **110** in which section **130** is 100 meters long and the active material in the gain medium of section **130** is GeO_2, and in which section **140** is 20 meters long and the active material in the gain medium of section **140** is P_2O_5. Reflectors **160** and **170** reflect 100% of energy impinging thereon at wavelength λ_{s1}. Reflector **180** reflects 100% of energy impinging thereon at wavelength $\lambda_{s1'}$, and reflector **190** reflects about 80% of energy impinging thereon at wavelength $\lambda_{s1'}$. The power at wavelength λ_p is 3 Watts upon entering optical fiber **110**. Reflectors **180** and **310** are disposed immediately adjacent point **150**.

[0065] Fig. 3A shows that the power of λ_p decreases as it propagates across section **130** from a value of 3 Watts upon entering fiber **110** to a value of about 0.5 Watt at point **150**. The power of λ_p continues to decrease as it propagates in the reverse direction from point **150**, reaching a value of about 0.1 Watt at the end of fiber **110** where the pump energy enters fiber **110**.

[0066] Fig. 3B shows that the power of λ_{s1} increases as it propagates in the forward direction across section **130**, starting at a value of about 2.3 Watts at the point where the pump energy enters fiber **110** and obtaining a value of about 3.5 Watts at point **150**. The power of λ_{s1} increases as it propagates in the reverse direction, starting at a value of about 0.4 Watts at point **150** and obtaining a value of about 2.3 Watts at the point where the pump energy enters fiber **110**.

[0067] A portion of the energy at wavelength λ_{s1} propagating in section **140** in both the forward and reverse directions is transferred to energy at wavelength $\lambda_{s1'}$. As a result, the power of λ_{s1} decreases as energy at wavelength λ_{s1} propagates in both the forward and reverse directions through section **140** (Figs. 3B and 3C).

[0068] Fig. 3C shows that the power of $\lambda_{s1'}$ increases as it propagates in the forward direction across section **140** from a value of about 10.8 Watts at point **150** to a value of about 12 Watts at the end of fiber **110**. The power of $\lambda_{s1'}$ increases as it propagates across section **140** from a value of about 9.6 Watts at the end of fiber **110** to a value of about 10.8 Watts at point **150**.

[0069] Fig. 4 shows an embodiment of a Raman fiber laser system **400** in which reflector **310** is not present in optical fiber **110**. Eliminating reflector **310** may be desirable, for example, when the power of wave λ_p is sufficiently low enough at point **150** that the amount of energy created at λ_u does not substantially interfere with the desired performance of the system.

[0070] Fig. 5 shows an embodiment of a Raman fiber laser system **500** in which suppressor **410** is not present in optical fiber **110**. Eliminating suppressor **410** may be desirable, for example, when the power of wave λ_{s1} is sufficiently low enough in section **130** of fiber **110** that the amount of energy created at λ_{s2} (and/or energy at higher order Raman Stokes shifts for the active material in gain medium **210**) does not substantially interfere with the desired performance of the system.

[0071] Fig. 6 shows an embodiment of a Raman fiber laser system **600** in which neither reflector nor suppressor **410** are present in optical fiber **110**.

[0072] Fig. 7 shows an embodiment of a Raman fiber laser system **700** that includes a suppressor **710** in section **140** of optical fiber **110**. Suppressor **710** is designed to suppress the formation of energy at higher order Raman Stokes shifts for the active material in gain medium **215** (e.g., energy at one or more $\lambda_{s2'}$, $\lambda_{s3'}$, $\lambda_{s4'}$, etc.). Suppressor **710** can be, for example, an LPG having its resonance frequency at $(c/\lambda_{s2'})$, where $\lambda_{s2'}^{-1} = \lambda_{s1'}^{-1} - \lambda_{r'}^{-1}$. The presence of suppressor **710** in section **140** may be desirable, for example, when the power of wave $\lambda_{s1'}$ in section **140** is sufficiently high that the power of wave $\lambda_{s2'}$ (and/or energy at higher order Raman Stokes shifts for the active material in

gain medium **215**) that would form in section **140** in the absence of suppressor **710** would substantially interfere with the desired performance of the system. System **700** can optionally include reflector **310** and/or suppressor **410**.

[0073] While the systems represented in Figs. 1 and 3-7 have shown reflectors and/or suppressor(s) having particular locations within optical fiber **110**, it is to be understood that these components can have different locations (relative locations and/or absolute locations) within fiber **110**. For example, the relative positions of reflectors **170** and **190** can be reversed. As another example, reflector **310** can be located in section **140** of fiber **110**. As an additional example, reflector **180** can be disposed in section **130** of optical fiber **110** (e.g., to the right or left of point **150**), and/or reflectors **170** and **190** can be disposed to the right of section **140** (e.g., in another section of fiber spliced to the right of section **140** of fiber **110**). Combinations of these configurations can be used. Other locations of reflectors and/or suppressor(s) in fiber **110** are also contemplated.

[0074] Fig. 8 shows an embodiment of a Raman fiber laser system **800** having an optical fiber **810**. Optical fiber **810** has a first section **130** having a gain medium containing an active material, and a second section **140** having a gain medium containing an active material that can be different than the active material contained in the gain medium of section **130**, and a third section **820** having a gain medium containing an active material that can be different than the active material contained in the gain medium of section **140**. The active material in the gain medium of section **820** of fiber **810** can be the same as or different than the active material in the gain medium of section **130** of fiber **810**. Sections **140** and **820** are spliced together at region **850**.

[0075] Optical fiber **810** includes pairs of reflectors **160** and **170**, **180** and **195**, and also includes a pair of reflectors **830** and **840** (e.g., a pair of fiber Bragg gratings). Reflector **195** (e.g., a fiber Bragg grating) is designed to reflect substantially all (e.g., about 100%) energy at $\lambda_{s1'}$. Reflector **830** is designed to reflect substantially all (e.g., about 100%) energy at wavelength $\lambda_{s1''}$, and reflector **840** is designed to reflect a portion (e.g., less than about 98%, less than about 95%, less than about 90%, less than about

80%, less than about 70%, less than about 60%, less than about 50%, less than about 40%, less than about 30%, less than about 20%, less than about 10%) of energy at wavelength $\lambda_{s1''}$, where $\lambda_{s1''}^{-1} = \lambda_{s1'}^{-1} - \lambda_{r''}^{-1}$ and $(c/\lambda_{r''})$ is the Raman Stokes frequency shift for the active material in the gain medium section **820** of fiber **810**.

[0076] With this arrangement, as energy at λ_p enters optical fiber **810**, the energy propagates through section **130** and. creates energy at wavelength λ_{s1}. Energy at λ_{s1} then propagates through sections **130** and **140** in the forward direction until it reaches reflector **170** where it is reflected backward through sections **140** and **130**. Energy at λ_{s1} then propagates through sections **140** and **130** in the reverse direction until it reaches reflector **160** where it is reflected forward through sections **130** and **140**. Energy at λ_{s1} continues to propagate in fiber **810** in the forward and reverse directions between reflectors **160** and **170**.

[0077] As energy at λ_{s1} propagates through section **140** of fiber **810**, it creates energy at wavelength $\lambda_{s1'}$. Energy at $\lambda_{s1'}$ then propagates through sections **140** and **820** in the forward direction until it reaches reflector **195** where it is reflected backward through sections **820** and **140**. Energy at $\lambda_{s1'}$ then propagates through sections **820** and **140** in the reverse direction until it reaches reflector **180** where it is reflected forward through sections **140** and **820**. Energy at $\lambda_{s1'}$ continues to propagate in fiber **810** in the forward and reverse directions between reflectors **180** and **195**.

[0078] As energy at $\lambda_{s1'}$ propagates through section **820** of fiber **610**, it creates energy at wavelength $\lambda_{s1''}$. Energy at wavelength $\lambda_{s1''}$ propagating in section **820** in the reverse direction is reflected by reflector **830** and then propagates through section **820** in the forward direction. Energy at wavelength $\lambda_{s1''}$ propagating through section **820** in the forward direction impinges on reflector **840**. Some of the energy at wavelength $\lambda_{s1''}$ impinging on reflector **840** is reflected by reflector **840** and then propagates through section **820** in the reverse direction, and some of the energy at wavelength $\lambda_{s1''}$ impinging on reflector **840** passes through reflector **840** and exits fiber **810**.

[0079] Fig. 9 shows a Raman fiber laser system **900** that includes reflector **310** in section **130** of fiber **810**. Fig. 10 shows a Raman fiber laser system **1000** that includes a suppressor **410** in section **130** of fiber **810**. Fig. 11 shows a Raman fiber laser system **1100** that includes a suppressor **1110** in section **140** of fiber **810**. Suppressor **1110** can be, for example, an LPG with a resonance frequency of $(c/\lambda_{s1'})$. Fig. 12 shows a Raman fiber laser system **1200** having suppressors **410** and **1110**, and reflector **310**.

[0080] Fig. 13 shows an embodiment of a Raman fiber laser system **1300** that includes a suppressor **1310** in section **820** of optical fiber **110**. Suppressor **1310** is designed to suppress the formation of energy at higher order Raman Stokes shifts (e.g., one or more of $\lambda_{s2''}$, $\lambda_{s3''}$, $\lambda_{s4''}$, etc.). Suppressor **1310** can be, for example, an LPG having its resonance frequency at $(c/\lambda_{s2''})$, where $\lambda_{s2''}^{-1} = \lambda_{s1''}^{-1} - \lambda_{r''}^{-1}$. The presence of suppressor **1310** in section **820** may be desirable, for example, when the power of wave $\lambda_{s1''}$ in section **820** is sufficiently high that the power of wave $\lambda_{s2''}$ (and/or energy at higher order Raman Stokes shifts for the active material in the gain medium of section **820** of fiber **810**) that would form in section **820** in the absence of suppressor **1310** would substantially interfere with the desired performance of the system. System **1300** can optionally include reflector **310**, suppressor **410** and/or suppressor **1110**.

[0081] While Figs. 8-13 show the reflectors and/or suppressor(s) having particular locations within optical fiber **810**, it is to be understood that these components can have different locations (relative locations and/or absolute locations) within fiber **810**. For example, the relative positions of reflectors **195** and **840** can be reversed. As another example, reflector **310** can be located in section **140** of fiber **810**. As an additional example, reflector **170** can be disposed in section **820** of fiber **810**. As a further example, reflector **180** can be disposed in section **130** of fiber **810**. Combinations of these configurations can be used. Other locations of these components in fiber **810** are also contemplated.

[0082] While embodiments have been shown in which sections **130, 140** and **820** are spliced together, the invention is not limited in this sense. Generally, sections **130,**

140 and/or **820** are spliced together if they are formed of different materials. When sections **130**, **140** and **820** are formed of the same materials, splicing is not required.

[0083] While Raman fiber lasers and Raman fiber laser systems having an optical fiber with two or three sections have been described, the invention is not limited to these systems. In general, an optical fiber can have N sections, where N is an integer (e.g., 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, etc.).

[0084] Moreover, while Raman fiber lasers and Raman fiber laser systems have been described with particular arrangements of active material in their respective gain media, other arrangements are also possible. In general, each section of the optical fiber can have a gain medium with an active material which can be the same or different than the active material in the gain medium of the neighboring section(s) of the fiber. In some embodiments, all sections of the optical fiber have a gain medium with the same active material. In certain embodiments, each section of the optical fiber has a gain medium with a different active material than the active material in the gain medium of the other sections. In some embodiments, the active material in the gain medium of neighboring sections can alternate. For example, a three-section optical fiber can be formed in which the active material in the gain medium of the first and third sections is the same, and in which the active material in the gain medium in the middle section is different. Other arrangements are contemplated.

[0085] Furthermore, while Raman fiber lasers and Raman fiber laser systems have been described in which sections of the optical fiber are spliced together, the invention is not limited in this sense. Generally, the sections of fiber are coupled together so that energy can propagate therebetween. Typically, the sections of fiber are contiguous. For example, in some embodiments, two neighboring sections of the optical fiber can have an interferometric connection. In certain embodiments, two neighboring sections of the optical fiber can be connected by a lens (e.g., a Green lens).

[0086] A typical design of a Raman fiber laser having N sections of optical fiber

is as follows. The section of fiber closest to where the pump energy at wavelength λ_p enters the fiber has a reflector designed to reflect substantially all (e.g., about 100%) energy at λ_{s1}. The section of fiber furthest (the N^{th} section of the fiber) from where the pump energy λ_p enters the fiber has three reflectors. One reflector is designed to partially reflect energy at λ_{s1n} (i.e., the desired wavelength of energy created by the system in the N^{th} section of the fiber), where $\lambda_{s1n}^{-1} = \lambda_{s1(n-1)}^{-1} - \lambda_{rn}^{-1}$, $\lambda_{s1(n-1)}$ is the desired wavelength of energy created by the system in the $(N-l)^{th}$ section of the fiber, and (c/ λ_{rn}) is the Raman Stokes shift frequency for the active material in the N^{th} section of the fiber. Another reflector in section N is designed to reflect substantially all (e.g., about 100%) energy propagating in the N^{th} section at λ_{s1n}. The other reflector in section N is designed to reflect substantially all (e.g., about 100%) energy propagating in the N^{th} section at $\lambda_{s1(n-1)}$ (i.e., the desired wavelength of energy created by the system in the $(N-l)^{th}$ section of the fiber), where $\lambda_{s1(n-1)}^{-1} = \lambda_{s1(n-2)}^{-1} - \lambda_{r(n-1)}^{-1}$, $\lambda_{s1(n-2)}$ is the desired wavelength of energy created by the system in the $(N-2)^{th}$ section of the fiber, and $(c/ \lambda_{r(n-1)})$ is the Raman Stokes shift frequency for the active material in the $(N-l)^{th}$ section of the fiber.

[0087] For any remaining sections of fiber (generically referred to as the M^{th} section of fiber, where M is an integer greater than one and less than N), each section has two reflectors. One reflector is designed to reflect substantially all (e.g., about 100%) energy propagating in the M^{th} section at wavelength λ_{s1m} (i.e., the desired wavelength of energy created by the system in the M^{th} section of the fiber), where $\lambda_{s1m}^{-1} = \lambda_{s1(m-1)}^{-1} - \lambda_{rm}^{-1}$, $\lambda_{s1(m-1)}$ is the desired wavelength of energy created by the system in the $(M-1)^{th}$ section of the fiber, and (c/ λ_{rm}) is the Raman Stokes shift frequency for the active material in the M^{th} section of the fiber. The other reflector is designed to reflect substantially all (e.g., about 100%) energy propagating in the M^{th} section at wavelength $\lambda_{s1(m-1)}$ (i.e., the desired wavelength of energy created by the system in the $(M-l)^{th}$ section of the fiber), where $\lambda_{s1(m-1)}^{-1} = \lambda_{s1(m-2)}^{-1} - \lambda_{r(m-1)}^{-1}$, $\lambda_{s1(m-2)}$ is the desired wavelength of energy created by the system in the $(M-2)^{th}$ section of the fiber and $(c/ \lambda_{r(m-1)})$ is the Raman Stokes shift frequency for the active material in the $(M-1)^{th}$ section of the fiber.

[0088] Each section of fiber can optionally include a suppressor (e.g., an LPG with a resonance frequency corresponding to energy at an undesired higher order Raman Stokes shift energy).

[0089] The system can optionally include a reflector designed to reflect substantially all (e.g., about 100%) energy impinging thereon at wavelength λ_p.

[0090] While certain embodiments of a Raman fiber laser having N sections of optical fiber have been described, it is to be understood that the invention is not limited to these embodiments. For example, the relative positioning of the reflectors and/or suppressor(s) can be modified (e.g., in a similar manner to that noted above). Other embodiments are also contemplated.

[0091] Generally, an optical fiber having N sections can convert energy entering the optical fiber at a particular wavelength (e.g., λ_p) to energy exiting the optical fiber at a different (e.g., wavelength λ_{s1n}, where λ_{s1n} is the desired wavelength of energy created by the system in the N^{th} section of the fiber) with relatively high efficiency. In certain embodiments, fiber **110** can convert at least about 55% (e.g., at least about 60%, at least about 65%, at least about 70%, at least about 75%, at least about 80%, at least about 85%, at least about 90%, at least about 95%, at least about 98%) of the energy entering fiber **110** at one wavelength (e.g., λ_p) to energy exiting fiber **110** at a different wavelength (e.g., λ_{s1n}).

[0092] Optical fiber **110** can convert energy entering fiber **110** at a particular wavelength (e.g., λ_p) to energy exiting fiber **110** at wavelengths other than a desired output wavelength (e.g., at wavelengths other than λ_{s1n}) with relatively low efficiency. In certain embodiments, fiber **110** can convert at most about 45% (e.g., at most about 40%, at most about 35%, at most about 30%, at most about 25%, at most about 20%, at most about 15%, at most about 10%, at most about 5%, at most about 2%) of the energy entering fiber **110** at a particular wavelength (λ_p) to energy exiting fiber **110** at wavelengths other than a desired wavelength (e.g., λ_{s1n}).

[0093] While certain embodiments have been described, the invention is not limited to these embodiments. For example, one or more sections of an optical fiber can be substantially devoid of a gain medium having an active material. As a further example, the reflectors need not be in the form of fiber Bragg gratings. For example, one or more of the reflectors can be a loop mirror, or one or more reflectors can be in the form of a coated mirror (e.g., a coated mirror at one or both ends of a section of optical fiber). As another example, the suppressor(s) need not be in the form of LPG(s). For example, one or more of the suppressors can be in the form of gratings (e.g., short period gratings) that are substantially nonperpendicular to the length of the fiber along which energy propagates. In these embodiments, the angle and/or period of the gratings can be selected to scatter one or more wavelengths of interest (e.g., one or more higher order Raman Stokes shift wavelengths). As an additional example, the type of laser used for pumping can be varied. Examples of lasers that can be used include semiconductor diode lasers (e.g., high power semiconductor diode lasers), double clad doped fiber lasers, conventional free space coupled lasers, and the like. As another example, various types of optical fibers can be used, including, for example, double clad optical fibers and polarization maintaining optical fibers. Furthermore, the optical fibers can be formed of, for example, silica based materials (e.g., fused silica based) or fluoride-based materials. As yet another example, the relative and/or absolute lengths of one or more of the sections of the optical fiber can be varied based upon the intended use of the Raman fiber laser.

[0094] Moreover, while the fibers and systems have been described as Raman fiber lasers and Raman fiber laser systems, those skilled in the art will appreciate that the general concepts described can be extended to provide amplifiers and amplifier systems. Generally, a fiber amplifier provides gain for energy at a wavelength of interest without the use of a lasing cavity (e.g., without a resonator) or with an optical cavity operating below lasing threshold. Fig. 14 is a schematic view of an embodiment of a fiber amplifier system **1400** in which fiber **1500** is used as a signal amplifier. Fiber **1500** contains multiple sections (e.g., as described above but having at least one section, such as the section adjacent the signal output, operating below lasing threshold). To operate at

below lasing threshold, for example, one or more of the reflectors can be removed from fiber **1500** and/or the reflectivity of one or more of the reflectors can be reduced. An input signal enters system **1400** via fiber **1101**. Energy source **1201** emits a pump signal **1301**. The input signal in fiber **1101** and pump signal **1301** are coupled into fiber **1500** via coupler **1401**. Such couplers are known to those skilled in the art. Pump signal **1301** interacts with the active material(s) in the sections of fiber **1500**, and the input signal is amplified. A device **1900** (e.g., an isolator) separates the amplified input signal from the Stokes shifted pump signal so that the Stokes shifted pump signal travels along fiber **1800**, and the amplified input signal travels along fiber **1950**. While Fig. 14 shows one embodiment of fiber **1500** in a fiber amplifier system, other fiber amplifier systems in which fiber **1500** can be used will be apparent to those of skill in the art.

[0095] Other embodiments are in the claims.